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Low-carbon electricity production through the implementation of photovoltaic panels in rooftops in urban environments: A case study for three cities in Peru

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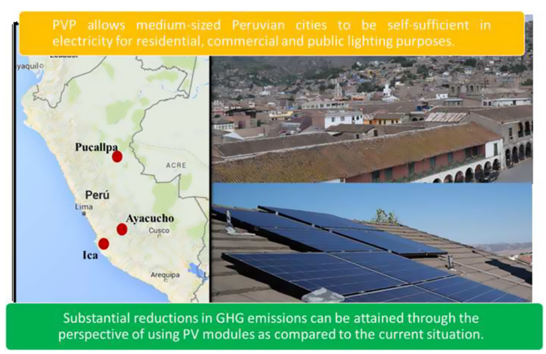
HIGHLIGHTS

- The solar energy potential of underutilized urban rooftops in Peru was analyzed.
- A model was elaborated for medium-sized Peruvian cities with GIS.
- Life Cycle Assessment was used to compute environmental impacts.
- Results demonstrate that self-sufficiency in electricity production is attainable.
- Substantial climate change mitigation could be accomplished with this layout.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban environments in Latin America must begin decarbonizing their activities to avoid increasing greenhouse gases (GHGs) emissions rates due to their reliance on fossil fuel-based energy to support economic growth. In this context, cities in Latin America have high potential to convert sunlight into energy. Hence, the main objective of this study was to determine the potential of electricity self-sufficiency production and mitigation of GHG emissions in three medium-sized cities in Peru through the revalorization of underutilized rooftop areas in urban environments. Each city represented a distinct natural area of Peru: Pacific coast, Andean region and Amazon basin. More specifically, photovoltaic solar systems were the technology selected for implementation in these rooftop areas. Data on incident solar energy, temperature and energy consumption were collected. Thereafter, ArcGis10.3 was used to quantify the total usable area in the cities. A series of correction factors, including tilt, orientation or roof profiles were applied to attain an accurate value of usable area. Finally, Life Cycle Assessment was the methodology chosen to calculate the reduction of environmental impacts as compared to the current context of using electricity from the regional grids. Results showed that the cities assessed have the potential to obtain their entire current electricity demand for residential, commercial and public lighting purposes, augmenting energy security and resilience to intermittent natural disasters, with the support of decentralized storage systems. This approach would also translate into substantial reductions in terms of GHG emissions. Annual reductions in GHG emissions ranged from 112 ton CO_2eq in the city of Ayacucho to over 523 kton CO_2eq in Pucallpa,

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showing that cities in the Amazon basin would be the ones that benefit the most in terms of climate change mitigation.

1. Introduction

Cities concentrate a high percentage of the world's population and economic activity. The United Nations (UN) has projected an urban population of more than 6500 million for year 2050 due to urbanization (Ferroukhi et al., 2015; UN, 2016). According to the Inter-American Development Bank (IDB), reaching sustainable urban growth is still an important challenge and implies the development of innovative decisions that should not compromise the welfare of future generations (IDB, 2011). Moreover, the urbanization process is one of the most important indicators of change in productivity in the global economy (Floater et al., 2014). Much of the global economy is generated in cities through economic activities, services and permanent communication channels. For instance, in Latin America and the Caribbean (LAC), eminently rural nations have developed in few decades into economies in which cities host 80% of the total population with a subsequent key role in the generation of wealth, approximately 70% of the Gross Domestic Product – GDP (Bárcena, 2001; IDB, 2011).

Processes that are carried out in cities require energy, water and food (i.e., the so called energy-water-food nexus), three essential resources which tend to come from external sources that generate great amount of GHG emissions, as well as other environmental impacts (Norman et al., 2006; Kennedy et al., 2009; National Academies of Sciences, Engineering, and Medicine, 2016). In this context, urban metabolism was defined by Kennedy et al. (2007) as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". Similarly, in a more recent study, Kennedy et al. (2014) defined urban metabolism as "a scientific phenomenon comprising individual processes that occur in all cities at different spatial and temporal scales". The importance of urban metabolism resides in the fact that it allows building inventories at a macro-scale for different urban sizes, since these macro-flows are usually not well aggregated or available. Thereafter, urban metabolism allows quantifying the material and energy flows that enter or exit urban environments (Delgado et al., 2012; UN-ESCWA, 2016). These flows can then be combined with other methodologies, including spatial methods (e.g., GIS), environmental methods (i.e., Life Cycle Assessment – LCA, Water Footprint, etc.) or management and economic methods in order to obtain further insights regarding urban dynamics (Sudhira et al., 2004; Choi et al., 2011; Vázquez-Rowe et al., 2014).

A study carried out by Gouldson et al. (2014) in five cities worldwide, including Peru's capital city, Lima, suggested that investing in low carbon policies such as local renewable energy or efficient public transport significantly reduces energy consumption and GHG emissions in a range of 10% to 24% in a period of 10 years. Moreover, if these policies were to be replicated in others cities, it is estimated that an 18% reduction in GHG emissions linked to use of energy could be attained in urban environments worldwide (Gouldson et al., 2014). Hence, the transition to low-carbon energy systems to feed urban environments appears as an important way forward to improve the environmental sustainability of cities, while fostering energy security (Jansen and Seebregts, 2010; UN-ESCWA, 2016; Wu et al., 2016). The importance of Gouldson et al. (2014) is linked to the fact that it is the only published study in which there is an attempt to apply urban metabolism to a Peruvian city. Decentralized renewable energy systems included in urban contexts allow the reduction of energy imports from far away sources. Furthermore, if energy security is attained, urban economic activities would not be completely interrupted in a situation in which centralized energy systems may fail, such as earthquakes or abnormal climatic events (Vázquez-Rowe et al., 2017). Other studies have also highlighted the appropriateness of installing small-scale low-carbon energy production in urban environments (Akella et al., 2009; Mastrucci et al., 2014; Ranaboldo et al., 2014). More specifically, Girardin et al. (2010) showed the viability of implementing endogenous energy production systems at a district level in Geneva, whereas Hofierka and Kaňuk (2009) determined that the use of photovoltaic solar modules in a small city in eastern Slovakia could cover two thirds of the city's electricity consumption.

Regardless of the benefits of renewable energy to allow cities to continue meeting their ever-growing energy demand, in a world in which climate-related and other environmental problems are emerging these hazards have become a challenge for cities, especially in developing and emerging nations in which investments in early warning systems or preventive infrastructure are scarce, and urban expansion can be rapid and informal (Goldstein et al., 2000; Basher, 2006). Therefore, redesigning urban metabolism models is consistent with decisions that do not compromise the well-being of current and future generations.

In the particular context of Peru, a country that is highly vulnerable to seismic and hydro-meteorological natural disasters, the sustainable development of cities represents a great challenge in terms of urban planning and policy-making (Leff et al., 2003). In fact, the extreme weather events that coastal Peru suffered in early-2017 due to an abnormal rise in ocean surface temperature caused serious damage in national infrastructure, including collapsed bridges and buildings (The Guardian, 2017; Vázquez-Rowe et al., 2017). Less impressive for mass media, but equally preoccupying, was the fact that these episodes disrupted the operation of centralized water and electricity production systems, as well as the distribution of these, with many major cities (e.g., Lima, Arequipa, Ica or Chiclayo) being left without water and/or electricity for several days (Perú21, 2017). These events showed the vulnerability of centralized energy systems and the need to build a more heterogeneous strategy to enhance disaster risk management policies. In this sense, decentralized urban systems may provide energy and water security when centralized systems fail (Massoud et al., 2009; Peter-Varbanets et al., 2009; Romero-Lankao et al., 2017).

However, the change in model would require the convergence in the urban environment of internalizing environmental costs, resolving social inequities and addressing financial constraints (Winchester, 2006; Ferroukhi et al., 2015). In other words, efforts must be placed to gradually abandon a model of dependency that Peruvian cities have adopted through time, without considering the potential that resides within the geographical boundaries of a given city (Leff et al., 2003). This issue is of particular importance in terms of energy flows, since the Peruvian national grid depends mainly on two energy sources: i) a hydropower sector that is becoming increasingly fragile due to changing patterns in terms of precipitation and a critical melting rate of glacial ice in the Peruvian *nevados* (Baraer et al., 2012; Schauwecker et al., 2014 and López-Moreno et al., 2014); and, b) a thermoelectric system that is based on burning fossil fuels, mainly domestically-extracted natural gas, with the evident impact in terms of GHG emissions (Vázquez-Rowe et al., 2015).

Considering that Peru will have to guarantee water supply for irrigation and human consumption in the hyper-arid, but heavily populated coastal area, and that it has recently signed the Treaty of Paris to reduce GHG emissions by 31% in 2030 (MINAM, 2015), it is imperative that urban environments in the country shift to cleaner and less vulnerable energy sources (Vázquez-Rowe et al., 2015). Therefore, the main objective of this study was to quantify the potential energy self-sufficiency in

Peruvian cities, focusing on the potential of urban photovoltaic generation in relation to the total electricity demand. In addition, the associated reduction in GHG emissions, using urban renewable energy systems. For this particular study, three medium-sized cities, each one of them located in a different geographical region of Peru, were selected: Ica, along the Peruvian coast, Ayacucho, in the southern highlands and Pucallpa in the Amazon basin.

The production of energy from non-conventional renewable sources in urban areas, mainly solar and wind power depends on the location of the city. In the case of wind energy, the minimum speed that allows wind turbines to produce electric energy must be at least 10 m/s; otherwise the implementation is not feasible. Moreover, the installed wind turbines in buildings should be designed based on the type of flow, direction and average wind speed (Chong and Naghavi, 2011). In most Peruvian cities, particularly those analyzed in the case study, the average wind speed does not exceed 6 m/s (SENAMHI, 2017). Hence, the use of this source of energy for electric power production was discarded.

Based on the requirements to apply wind energy technology in urban environments, in which the roughness of the terrain reduces wind speed (Dayan, 2006), and considering the high potential to convert sunlight into solar energy in most of Peru (SENAMHI, 2015), these cities were analyzed just through the implementation of photovoltaic solar systems. This system includes modules and batteries, in commonly underutilized areas, urban rooftops, with the aim of identifying to what extent they could become self-reliant on energy. Total available area was calculated with a Geographic Information System (GIS), in this case ArcGIS 10.3. Thereafter, the environmental impact was quantified with the use of the Life Cycle Assessment (LCA) methodology, which allowed comparing the production of these photovoltaic systems with the current scenario in which all the electricity is obtained from the national grid. The scope of the study did not include an economic analysis. However, such analysis is relevant to evaluate feasibility of the transition to decentralized renewable energy systems (Chen et al., 2011.) and will be tackled in future research. The study is intended to be of utility for policy-makers at a local, regional and national level, since it may be used as a starting point to transform energy flows in Peruvian cities. Moreover, the small but thriving renewable energy corporate sector in Peru may also benefit from this discussion.

2. Materials and methods

2.1. Selection of urban environments

Rooftops were chosen as the urban areas in which to implement the photovoltaic panels due to the opportunity to revalorize these underutilized areas. For this, a first step that was conducted was to characterize the three selected cities from an environmental, social and economic perspective. On the one hand, data related to the potential of renewable energy in each city were analyzed; particularly photovoltaic solar energy concentrated the interest of this study. For this, a series of climatic data was needed for each of the cities selected. On the other hand, economic and social aspects, which are closely linked to energy consumption, together with population density and growth were considered.

Peru is one of the most diverse countries in the world in terms of climates across its geography (Mittermeier et al., 1998). However, these tend to be grouped into three main natural areas: the hyper-arid Peruvian Pacific coast, the highlands in the Andes and the Amazon basin. Therefore, the selection of urban environments to study their energy potential was based on choosing a representative city in each of these natural areas. In this context, medium-sized cities were considered in which local authorities willingly provided energy-relevant data to conduct the analysis. Hence, Ica (14°04′S; 75°44′W), located 250 km South of Lima, was the coastal city selected. Its population is growing fast thanks to a buoyant agricultural sector, which, despite its hyper-arid climate, relies on coastal aquifers and rainfall from the Andes. For the highlands, the chosen city was Ayacucho (13°09′S; 74°13′W) with moderate precipitation and a relatively high number of annual hours of sun. Finally, in the Amazon basin the city of Pucallpa was selected (8°23′S; 74°33′W), which presents typical rainforest climate conditions. Fig. S1 in the Supporting material (SM) presents the geographical location of the cities selected and climatic region (Pulgar-Vidal, 2014). The main socio-economic characteristics for the three cities can be observed in Table 1.

2.2. Data acquisition

Data required to model the desired energy self-sufficiency potential in the three cities included a range of demographic and climate indicators. In the first place, demographic data were obtained for the case studies, including population density, total population and the size of the municipalities that are included in the boundaries of each city (INEI, 2015). Secondly, electricity consumption was provided by local electric companies on a monthly basis (Electro Dunas, Electrocentro and Electro Ucayali, personal communication, July 2016). As shown in Fig. 1, these values, which are referred to the period 2010–2015, were transformed into average annual per capita consumption. It should be noted that total electricity consumption included residential, commercial and public lighting uses, but excluded industrial use of electricity. Hourly data linked to electricity demand on a daily basis was not provided by local electric companies. However, the average daily distribution for Peru is shown in Fig. S2 of the SM. The latter allowed approximating the capacity needed in batteries.

Regarding climate data, incident solar energy was computed in order to identify how much energy can be produced per unit area of surface in a given geographical region. This indicator is critical in terms of understanding the importance of solar energy in a specific location. Fig. 2 shows the incident solar energy per month in each of the three cities selected based on data provided by the Peruvian Meteorological Institute (SENAMHI) and the Ministry of Energy for the period 2010–2014 (SENAMHI, 2015). These data were retrieved from the closest meteorological stations for each city in order to account for more precise information than that obtained from solar maps. For further information, Fig. S3 in the SM shows the solar maps at national scale on a seasonal basis. Data show that incident solar energy is substantially higher than in countries were photovoltaic energy has grown the most in the past decade, such as Spain (5.5 kWh/m^2), China (5.5 kWh/m^2) or Germany (4.5 kWh/m^2) (AEMET – Spanish Meteorological Agency, personal communication, May 2017; SolarGis, 2017). Finally, temperature data, including average values, as well as maximum and minimum temperatures, were obtained from SENAMHI in order to identify the efficiency of solar modules (SENAMHI, personal communication, May 2016). Maximum efficiency is achieved at 25 °C; if the temperature is lower or higher than this value, the efficiency of the modules starts to decrease directly proportional to the change in temperature. To account for this aspect, linearization was conducted for the computation. Fig. S4

Table 1
Main socioeconomic data for the cities of Ica, Ayacucho and Pucallpa.

	Unit	Ica	Ayacucho	Pucallpa
Municipal area[a]	km^2	1197	141	11,135
Total population[b]	pop.	244,390	183,896	211,651
GDP per capita[c]	USD	8967	6761	6737
Poverty[d]	%	8.6	43.8	17.9
Socioeconomic level[a,e]	–	C	C	C

[a] Data obtained from the Peruvian Central Bank (BCRP, 2016).
[b] Data obtained from the Peruvian Statistics Institute (INEI, 2012).
[c] Data obtained from the Peruvian Statistics Institute (INEI, 2015).
[d] Data obtained from the International Development Bank (IDB, 2012).
[e] Socioeconomic levels in Peru are ranked from A to E, being A the group with highest purchase power and group E the lowest one.

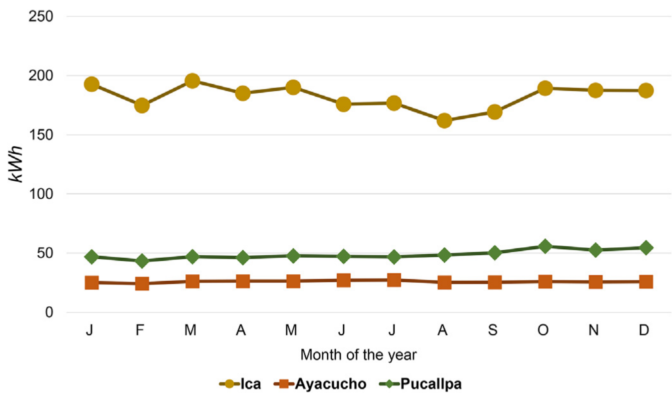

Fig. 1. Average monthly electricity consumption in the cities analyzed reported in kWh per capita in the period 2010–2015.

and Table S1 in the SM show the average values of temperature in each of the cities assessed.

2.3. Computation method for potential solar energy and spatialization

Once the data presented in Section 2.2 were aggregated, the required residential energy was calculated in kWh/m^2 to identify the amount of solar modules that need to be placed in the rooftops. Thereafter, ArcGis v10.3 was used to calculate the rooftop area available. To do so, a representative area of approximately 130 ha was selected in each case of study. This surface area was considered based on the typical grid plan of Peruvian cities to guarantee a representative sample of the basic unit of their urban planning: the city block. City blocks in Latin American nations usually have an average area of 80 by 80 m, which tend to be replicative throughout most formally-built areas of the city (Aguilar et al., 2003). In this sense, the three Peruvian cities assessed show a relatively standard configuration of their urban space in blocks, regardless of small historic centers, limited green space (LAGCI, 2010).

The selected areas in each city are shown in Fig. S5. These were chosen on the basis of two main criteria. On the one hand, areas with predominantly residential neighborhoods were identified, excluding the historic district. On the other hand, districts of the city with similar socioeconomic levels to the city average were used in the assessment. Therefore, the district of *Ica* was selected in Ica, *Ayacucho* in Ayacucho and *Callería* in the city of Pucallpa. Once the rooftop areas were computed for the selected polygon using ArcGis v10.3, this information was extrapolated to the entire size of the city.

The computed preliminary rooftop area for the entire cities, which coincides with the built up area, was 753 ha in the case of Ica, 585 for Ayacucho and 3869 ha in Pucallpa. Thereafter, a ratio was generated between the total population of the cities and the rooftop areas, which was later translated into electricity consumption per unit area (i.e., kWh/m^2). The final step in order to compute required residential energy was to use a correction factor of 0.75 in order to account for energy losses in the photovoltaic solar systems installed (Lorenzo, 2002).

Rooftop profiles can be very varied, affecting the disposition of the photovoltaic modules, as shown in Table 2. The size of the individual module assumed in this study was a conventional monocrystalline 1 m × 1.5 m piece, which is a standard dimension produced by solar energy companies (e.g., Soluxtec, Dokio, Onyx Solar) and the most common for use in urban design (Kahoul et al., 2017). Considering that the efficiency of the modules ranged from 15% to 18% based on the temperatures registered in the cities examined, the optimal energy provided per module was computed (Esperanza Cárdenas, Acciona Energía – Spain, personal communication, January 2017).

However, these modules cannot occupy the entire available space due to several reasons. In the first place, since a certain distance between modules must be respected, a 0.60 factor was considered for the city of Ayacucho, whereas for Ica and Pucallpa this factor was 0.72. The differing factors between cities depend on the shape of the roofs, as shown in Fig. 3. Secondly, a factor of 0.7 was assumed due to the lack of cleaning of these units (i.e., dust), that impedes an optimal utilization of incoming energy (Esperanza Cárdenas, Acciona Energía – Spain, personal communication, January 2017). A third issue of interest is the orientation of the modules. Although traditionally these were orientated towards the North in the southern hemisphere, recent studies suggest that the ideal orientation should be East or West (Hartner et al., 2015; Singh and Banarjee, 2015). Therefore, either of the latter was assumed in the current study. Finally, a fourth factor that should be taken into account is the tilt of the modules, which depends mainly on latitude. In the case of predominant flat rooftops (i.e., the city of Ica), optimum tilt was assumed to guarantee optimal efficiency (factor of 1), whereas in Ayacucho and Pucallpa a more conservative factor of 0.80 was considered (Hartner et al., 2015), based on the assumption that

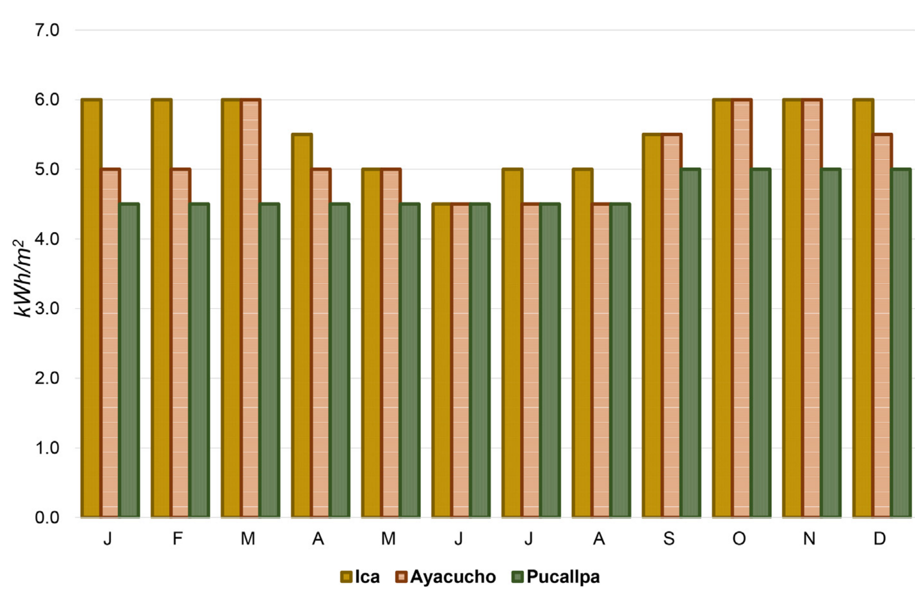

Fig. 2. Average daily incident solar energy in the cities analyzed for the period 2010–2014. Data reported in average kWh/m^2∗day for the entire period.

Table 2
Correction factors considered to calculate the placement and efficiency of photovoltaic solar panels.

Description	Factor	Observations
Rooftop profile	0.60–0.72	Data provided by Acciona Energía (2017, personal communication).
Cleaning (dust)	0.7	Data provided by Acciona Energía (2017, personal communication).
Interference	Depends on the representative area in each city.	ArcGis v10.3 and Google Earth.
Orientation[a]	Flat rooftop: 1.00. Inclined rooftop: depends on the representative area for each city.	ArcGis v10.3, Google Earth (Singh and Banarjee, 2015; Hartner et al., 2015)
Tilt	Flat rooftop: 1.00 Inclined rooftop: 0.80	ArcGis v10.3, Google Earth (Hartner et al., 2015)
Shading	Depends on a representative area for each city.	ArcGis v10.3, Google Earth (Hong et al., 2017)
Temperature/type of solar module	Depends on the variation of temperature above or below 25 °C	Data provided by Acciona Energía (2017, personal communication)

[a] Considers the optimal orientation towards the Sun during daytime.

the modules are installed with the same tilt as that of the roofs (Figs. 4 and 5).

When the placement of the panels is scaled to the 130 ha sample area in each city, two additional correction factors must be taken into consideration: interference and shading. For the former, Google Earth was used in combination with ArcGis to perform a series of iterations to identify unavailable rooftop areas due to permanent infrastructure or construction (e.g., ventilation ducts, water storage tanks, etc.). This iteration allowed calculating the real available rooftop in the representative area of each city, which was then extrapolated to the entire city. For this, maps elaborated for each city by the Peruvian Geographic National Institute (IGN) in CAD extension were transformed into SHAPE extension in ArcGis v10.3, as shown in Fig. S6 in the SM. For the latter, the shading areas projected on the roofs of buildings were calculated based on the difference in heights between adjacent buildings. In this sense, the rooftop areas were quantified using ArcGIS for the selected polygon and, thereafter, with Google Earth, the free shading area was computed counting each of the rooftops within the representative polygon. The quotient between the free shading area and total area was the correction factor for this correction factor.

Initially, through GIS the total rooftop area was calculated in the representative area selected. It is important to indicate that in Peruvian cities, as well as most Latin American cities, land use for residential activities is shared with commercial use. Hence, many stores mainly focused on distribution of products and services are located in buildings intended for housing. The IGN has modelled these areas dedicated to residential use in polygons. In fact, cadastral maps have information from the areas corresponding to the residential lots. Therefore, it is possible to make the sum of these areas using GIS to compute the total residential area available in the polygon selected. The final step, as can be observed in Fig. 6, is based on the calculation of the photovoltaic solar electricity potential that can be produced in the effective area for residential, commercial and public lighting. Fig. 6 is a flow chart where the steps of the methodology are displayed in a general form. On one hand, the upper part of the illustration considers the procedure to calculate the electric energy demand, whereas the bottom half indicates how the photovoltaic solar potential is quantified. Thereafter, the values obtained are compared with the required energy in order to obtain a self-sufficiency factor. In other words, Fig. 6 summarizes the procedure for calculating the self-sufficiency factor between the photovoltaic solar potential and the required energy in each city.

2.4. Environmental assessment of the case studies selected

The environmental assessment was carried out using the LCA methodology. For this, the ISO 14040/14044 framework was followed with the main purpose of monitoring the GHG emissions generated in the life-cycle of implementing the photovoltaic solar systems. Moreover, a comparative analysis with the current centralized electricity mix that nourishes the cities under assessment was provided. For both systems, an attributional perspective was conducted, accounting for a steady-state computation of the environmental impacts. In this context, the function of the system was to provide a certain amount of electric energy for residential, commercial or public lighting uses. Hence, an initial reference unit to which the environmental values were referred to was 1 kWh of electricity produced and available for consumption. Thereafter, the selected reference for the current and the projected scenarios were homogenized to kWh/m^2, in which the unit area corresponds to the total built up area of each town. Consequently, the functional unit used to refer the results was one square meter of residential area (i.e., rooftop area) in any of the cities selected. Fig. 7 summarizes the procedure to calculate the variation in GHG emissions between the electricity produced by the current electric grid and by the photovoltaic solar systems proposed in each city. The system boundary for the Peruvian centralized electricity system was the production of high voltage electricity and its delivery to the national grid. In contrast, for the decentralized photovoltaic systems, the production of the solar modules and batteries, their maintenance, operation and end-of-life were considered. These batteries allow storing energy

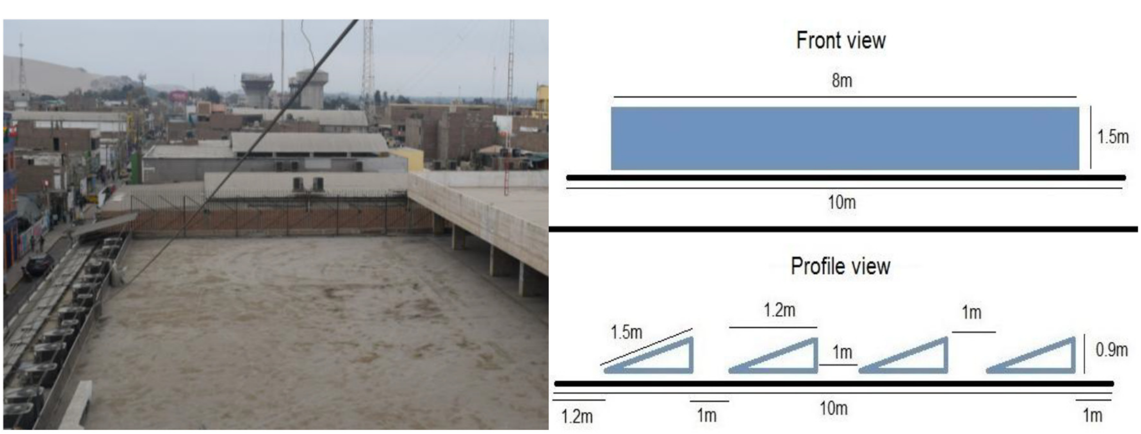

Fig. 3. Predominant rooftop profiles in the city of Ica.

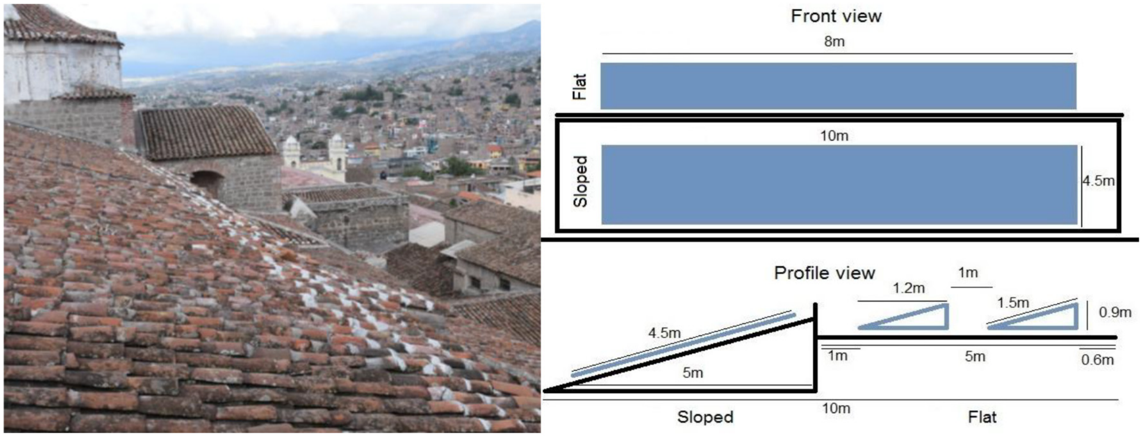

Fig. 4. Predominant rooftop profiles in the city of Ayacucho.

during the daytime that can then be used during the night hours. Lithium ion batteries were considered for the energy storage in the photovoltaic systems. Distribution of electricity and its conversion to medium or low voltage were excluded operations for the centralized system.

Data acquisition for the current scenarios of electricity production (i.e., electricity mix) was obtained from the Ministry of Energy and Mining (MINEM, 2011, 2012, 2013, 2014, 2015, 2016). A previous study by Vázquez-Rowe et al. (2015) had delved into the environmental impacts caused by electricity production in Peru in the period 1989–2013. However, in the current study it was decided to model the electricity mix of each Peruvian region individually, to account for regional variability. Hence, electricity production data were retrieved for the period 2010–2015. The average mix of this period was used in the development of the Life Cycle Inventory (LCI) to represent current production of electricity in the regions of Ica, Ayacucho and Ucayali (i.e., the region where Pucallpa is located). In the case of Ucayali and Ica energy production was dominated by thermoelectric power plants, 99% and 91%, respectively, in year 2014, whereas in Ayacucho 79% of the production was linked to hydropower generation in that same year. Modelling for the photovoltaic scenario was performed by using 3 kWp, single-Si photovoltaic modules, which include infrastructure. Moreover, Global Warming Potential (GWP) data used for lithium ion batteries were based on the results reported by McManus (2012), that is, 97.2 kg CO_2eq/kWh of capacity. Thus, the daily capacity required per city was quantified with the electricity consumption data and the curve of electric load for Peruvian cities presented in Fig. S2 in the SM.

Ecoinvent® was used as the database that supported the background data for the mathematical computation (ecoinvent®, 2017). Table 3 describes the process units that were included in the life cycle modelling. The assessment method used to compute the environmental impact results was IPCC 2013 – 100 years (IPCC, 2013). This method, which focuses exclusively on the environmental impacts linked to GWP, includes updated characterization factors for important GHGs, such as methane (CH_4) and dinitrogen monoxide (N_2O), as compared to previous methods. Finally, the software used to compute the results was SimaPro 8.3.0 (PRè-Consultants, 2017).

2.5. Sensitivity analysis

Certain variables that were assumed in the study are highly variable, with the subsequent influence on final results. For instance, in the calculation of intermediate values, it has been noted that aspects such as the residential population density, the efficiency of monocrystalline solar modules or the growth of the electric energy per capita consumption and population density may have significant impacts on the results (Chen et al., 2017).

Thus, it was necessary to analyze how the variation of these values determines the self-sufficiency of the cities by proposing alternative scenarios in the sensitivity analysis. In this context, four future scenarios

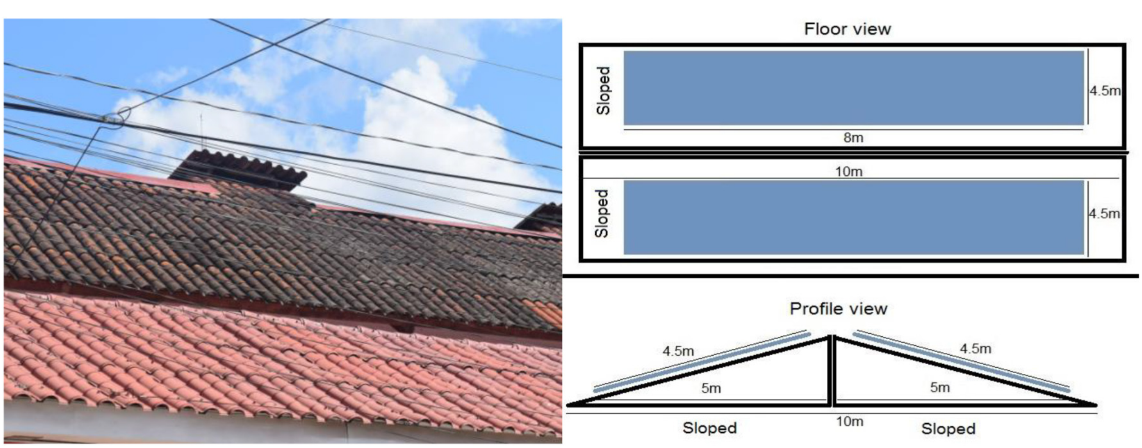

Fig. 5. Predominant rooftop profiles in the city of Pucallpa.

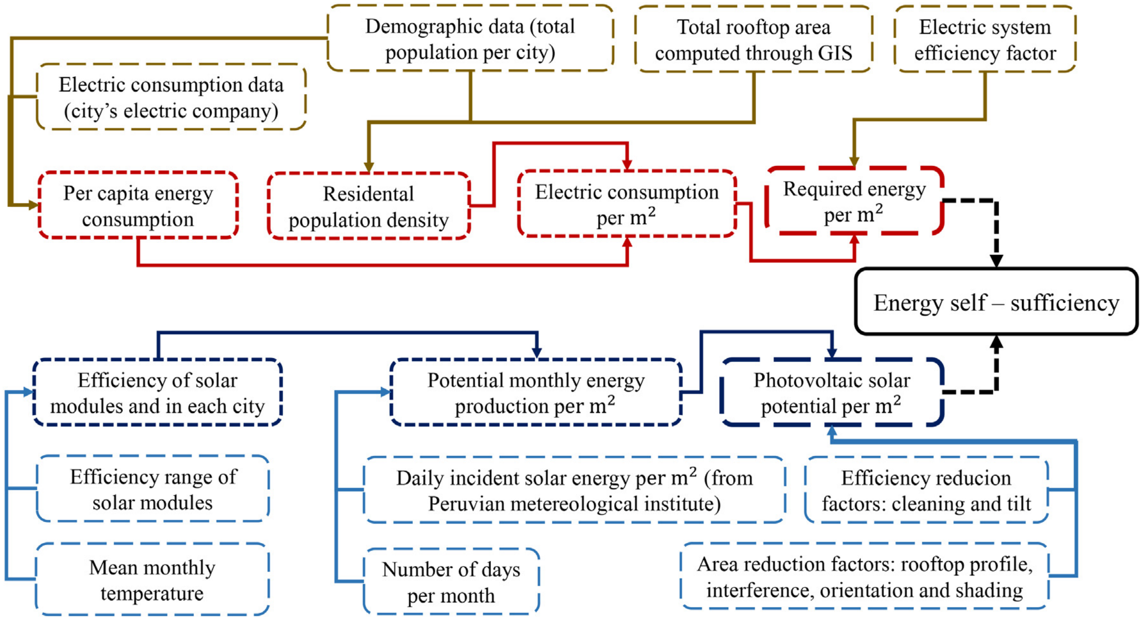

Fig. 6. Graphical representation of the procedure to calculate electricity self-sufficiency factor in the cities analyzed. Dotted lines represent intermediate calculations, whereas dashed lines represent final values; solid lines represent the final electricity self-sufficiency factor calculated in each city.

were defined for the sensitivity analysis. The scenarios have been expressed in the following way:

i) Scenario A1. Estimation of the maximum value of residential population density allowed in order to maintaining a monthly energy self-sufficiency factor not less than one.
ii) Scenario A2. Based on the technological advancement of photovoltaic solar panels, it is expected that in the short-term there will be modules with increased efficiency. For instance, at a laboratory scale, efficiencies of up to 22% have been achieved (Greentechmedia, 2017). Therefore, Scenario A2 assumes a 22% efficiency value for the solar modules.
iii) Scenario A3. This scenario is the result of the combination of the A1 and A2 scenarios, in which an increase in the efficiency of solar modules and critical residential population density are put together. Therefore, the objective of this scenario is to monitor the maximum value of residential population density allowed in order to maintaining a monthly energy self-sufficiency factor not less than one if the efficiency of solar modules is 22%.
iv) Scenario A4. This final scenario aims at predicting the self-sufficiency ratios that will be attained in the period 2030–2035. For this, the increase in electricity demand per capita and population density were observed on an annual basis in the period

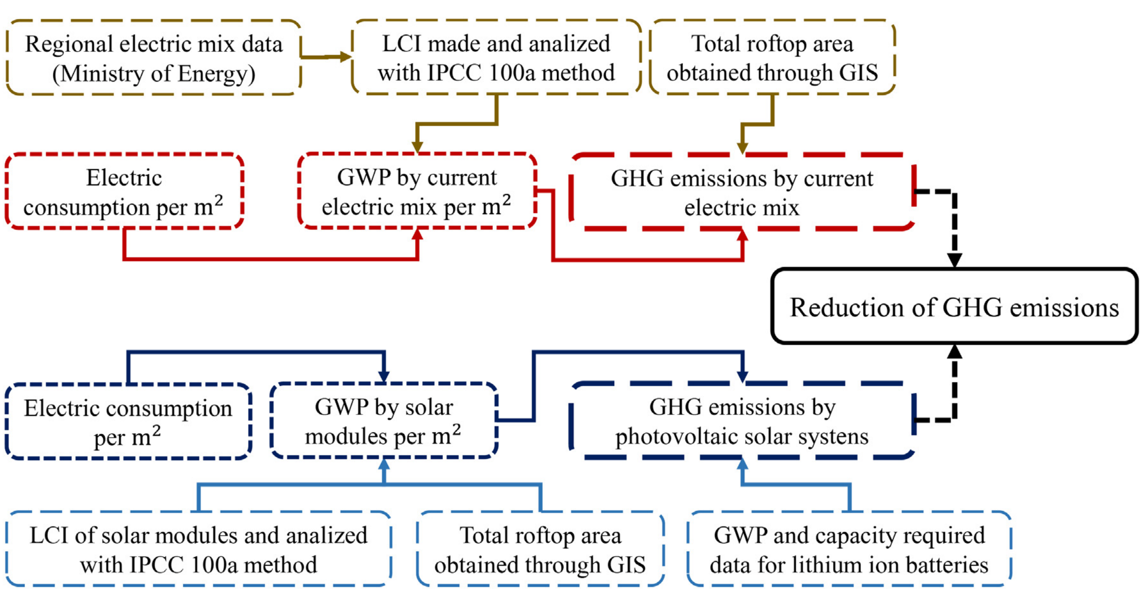

Fig. 7. Graphical representation of the procedure to calculate GHG emissions mitigation in the analyzed cities. Dotted lines represent intermediate calculations, whereas dashed lines represent final values; solid lines represent the GHG emission reductions computed in each city.

Table 3
List and description of the main dataset modifications that were performed for the computation of the results.

Dataset	Main database	Action taken
Electricity high voltage, regional production mix (Ica)	Ecoinvent® 3	The electricity production in the region of Ica was adapted based on the map of installed power and energy production reported by the Ministry of Energy (2010–2015).
Electricity high voltage, regional production mix (Ayacucho)	Ecoinvent® 3	The electricity production in the region of Ayacucho was adapted based on the map of installed power and energy production reported by the Ministry of Energy (2010–2015).
Electricity high voltage, regional production mix (Pucallpa)	Ecoinvent® 3	The electricity production in the region of Ucayali was adapted based on the map of installed power and energy production reported by the Ministry of Energy (2010–2015).
Photovoltaic 3 kWp, single - Si, panel, integrated on roof	Ecoinvent® 3	Typical commercial photovoltaic modules are adapted to urban production conditions, generally in underutilized areas, specifically roofs.

2010–2015 for each city. The highest annual increases were thereafter assumed as a proxy for the future tendency until 2035.

3. Results

3.1. Calculation of usable urban rooftop area

The initial rooftop area computed with ArcGis v10.3 was 6.47 ha for Ica, 17.64 ha for Ayacucho and 16.13 ha for Pucallpa (see Table 4). Thereafter, a first correction factor was applied to exclude areas where objects such as security walls, machines rooms, ventilation engines and other intrusive objects appeared. Hence, available rooftop area was cut down to 5.31 ha in Ica, 13.57 ha in Ayacucho and 13.52 ha in Pucallpa. A second correction factor consisted in excluding rooftop area in North-South orientation. Consequently, only rooftops with an East-West orientation have been considered. Consequently, a total of 5.31 ha were identified for Ica, 7.92 ha for Ayacucho and 5.62 ha for Pucallpa considering current city limits. A final correction had to be performed based on the fact that the uneven distribution of building heights in a city's skyline creates shading that must be accounted for. In a similar way as the iteration used for interference and orientation, rooftops that are prone to permanent shading were excluded from the area of interest, lowering the final available rooftop areas to 3.42 ha in Ica, 4.56 ha in Ayacucho and 4.03 ha in Pucallpa. Topography linked to the surrounding orography was not found to generate additional shading in the cities included in the case study, but may be an issue to be considered in other cities.

Table 5 presents the use of the factors previously described to calculate the total effective area available in each city to install photovoltaic solar modules. As observed, an aggregated correction factor of 0.38 was calculated for the city of Ica, a value that was substantially higher than that computed for Ayacucho (0.155) or Pucallpa (0.18). When these factors are applied to the final effective usable area in each city, it can be seen that Pucallpa would have nearly 700 ha of available rooftop area given the fact that it is more spread out than the other two cities (41.8 m^2 per person), with lower population density. Ica, with the highest aggregated correction factor and highest population density ($3.24E-2$ pop./m^2), would have 286 ha of usable rooftop area. On the other, Ayacucho, with the lowest aggregated correction factor, would present the lowest land area: 91 ha.

3.2. Electricity generation computation

Table 6 shows the efficiency correction factors for tilt and cleaning considered for the cities assessed. In the case of Ica, the correction factor for tilt was fixed at one considering that the vast predominant shape of rooftops in city is flat. In other words, solar modules in this particular case can be installed considering optimal tilt, which will depend on the latitude (geographical location) of the city assessed (Hartner et al., 2015). Furthermore, Table 6 also shows the computation of electricity obtained from photovoltaic sources quantified square meter. Thereafter, the total electricity generation potential with these modules is presented for the whole city and compared to the total required energy.

Results show that in all three cities the amount of produced electricity would be higher than the required electricity demand based on the historical series assumed in the case study. For instance, in the city of Ica a total of 662 GWh/year could be produced if all the usable area for solar modules in rooftops were operational. This value represents three times more energy than the current energy required in the city currently. For the case of Ayacucho, potential production is substantially lower due to less available area for solar modules and less energy potential per unit area. Even so, in a similar way to Ica, the city would have three times more potential to produce electricity than what it currently needs. Finally, Pucallpa shows the highest potential to produce solar energy (1165 GWh/year), partly linked to the fact that this city is more spread out than the other two. This value represents more than eight times more potential for solar energy production than electricity required for the city.

3.3. GHG emission reductions in the city of Ica

Fig. 8 shows the specific results obtained for the city of Ica. Throughout the entire year, the production of electricity from the photovoltaic solar systems would be substantially higher than the current required electricity demand, ranging from a factor of 2.64 in June to a factor of 3.71 in January. When translated into GHG emissions, reductions ranging from 72.3% to 73.9% can be attained each month, as compared to the use of the current electricity mix from the grid. For instance, GHG emissions per square meter of built up area in the current scenario have a minimum of 599.4 g CO_2eq in the month of August, as compared to a peak of 190.6 g CO_2eq in the month of March when using photovoltaic systems. When extrapolating to the entire city, these savings would imply a reduction of 44,786 ton CO_2eq per year.

Table 4
Correction factors and effective available rooftop area after each correction in the selected polygon.

	Unit	Effective area in the selected polygon in each city			Correction factors[a]		
		Ica	Ayacucho	Pucallpa	Ica	Ayacucho	Pucallpa
Initial rooftop area	ha	6.47	17.64	16.13	–	–	–
Rooftop area after interference correction	ha	5.31	13.57	13.52	0.821	0.769	0.838
Rooftop area after orientation correction	ha	5.31	7.92	5.62	1.000	0.584	0.416
Rooftop area after shading correction	ha	3.42	4.56	4.03	0.643	0.576	0.717

[a] The correction factors applied are dimensionless.

Table 5
Area correction factors and effective usable rooftop area quantification for photovoltaic solar modules in the cities selected.

	Area correction factors[a]			Unit	Effective area of the whole city		
	Ica	Ayacucho	Pucallpa		Ica	Ayacucho	Pucallpa
Rooftop area[b] (total city)				ha	753.2	585.5	3869.4
Population density[c]				pop./km^2	32,400	31,400	23,900
Rooftop profile	0.720	0.600	0.720	ha	542.3	351.3	2785.9
Interference	0.821	0.769	0.838	ha	445.3	270.1	2336.1
Orientation	1.000	0.584	0.416	ha	445.3	157.8	971.2
Shading	0.643	0.576	0.717	ha	286.3	90.9	696.4
Integrated area correction factor	0.380	0.155	0.180				
Final potential area				ha	286.3	90.9	696.4

[a] The correction factors applied are dimensionless.
[b] The rooftop area is equivalent to the built up area.
[c] Population density was calculated for the built up (rooftop) area, not for the entire area of the city limits.

3.4. GHG emission reductions in the city of Ayacucho

In the case of the city of Ayacucho, electricity production obtained with the projected low carbon scenario would also be substantially higher than the required electricity demand; with self-sufficiency factors ranging from 2.48 in June to 3.79 in October (see Fig. 9). In contrast, the reduction in GHG emissions is much lower per square meter of built up area than in the case of Ica, with reductions ranging from 1.8% to 6.3%. The reason behind this is the fact that the regional electricity mix in Ayacucho is linked mainly to the production of hydroelectricity (79%), whereas the use of thermal power plants represents a minor proportion of the total electricity generation. This implies that climate change environmental impacts linked to electricity use in Ayacucho are already low, and the implementation of solar panels in this city would not derive in such a significant reduction in GHG emissions.

3.5. GHG emission reductions in the city of Pucallpa

In the city of Pucallpa the self-sufficiency ratio was the lowest computed of the three cities, ranging from 1.92 in October to 2.14 in June (see Fig. 10). Despite this lower ratio, the implementation of solar modules in rooftops to cover its residential, commercial and public lighting electricity requirements would still fulfill electricity demand. Interestingly, Pucallpa has the highest impacts in terms of climate change regarding its energy grid, since it relies 99% on thermoelectric power stations. In fact, this is an issue that does not only affect Pucallpa and its region (Ucayali), but also the other two Peruvian regions that are located entirely in the Amazon basin: Loreto and Madre de Dios. Therefore, the reduction in GHG emissions that can be attained in the city of Pucallpa by installing photovoltaic solar systems was roughly 90% throughout all the year. In fact, if this scenario were to be implemented, the reduction in GHG emissions for the entire city could be as high as 522,763 ton CO_2eq per year, tenfold the savings that could be attained on an annual basis in Ica.

4. Discussion

4.1. Environmental relevance of the photovoltaic systems

The results show that despite the fact that all three cities attain self-sufficiency to cover the residential, commercial and public lighting demand for electricity throughout the year, mitigation of GHG emissions varies considerably between them depending on the electricity grid mix that is substituted. For instance, in the region of Ayacucho current electricity production is dominated by hydroelectric production. Hence, climate change mitigation through the proposed system is limited, since the annual GHG emissions per kWh of electricity generated ranged from 7 g CO_2eq in 2010 to 92 g CO_2eq in 2015, as compared to 91.0 g CO_2eq/kWh generated with the proposed solar systems in this city. However, it should be noted that in past years the use of fossil fuels to account for growing demand for electricity has increased substantially (Vázquez-Rowe et al., 2015). In contrast, in the city of Pucallpa all electricity is produced from fossil sources, with GHG emissions in all the examined years above 1.25 kg CO_2eq. If the different Peruvian cities are examined considering their location in the three natural areas, as well as the electricity matrix in each region, other cities located in the Amazon basin suffer from the same situation as Pucallpa, with their electricity grid being nourished with fossil fuels. Therefore, despite the fact that the potential for photovoltaic installation in rooftops is good in the three cities assessed, we argue that policy actions in this direction would be of increased interest in the Amazon basin, since the reductions in GHG emissions are substantially higher than in a coastal or Andean context.

Net annual GHG emissions reductions in the city of Pucallpa in the proposed model would add up to 522 kton of CO_2eq. Interestingly,

Table 6
Efficiency correction factors and quantification of the total electricity produced in each city with photovoltaic panels on rooftops.

	Efficiency correction factors[a]			Unit	PV potential and required energy in the city		
	Ica	Ayacucho	Pucallpa		Ica	Ayacucho	Pucallpa
Cleaning	0.7	0.7	0.7				
Tilt	1.0	0.8	0.8				
Integrated efficiency correction factor	0.700	0.560	0.560				
Annual photovoltaic electricity production (without corrections)				kWh/m^2	330.4	289.6	298.9
Annual photovoltaic electricity production (with correction factors)				kWh/m^2	87.89	25.17	30.12
Total potential energy produced				GWh/year	662.1	147.4	1165.4
Potential energy produced per capita				kWh per capita	2709	801.5	5506
Total required energy				GWh/year	209.2	48.56	136.8

PV: photovoltaic.
[a] The correction factors applied are dimensionless.

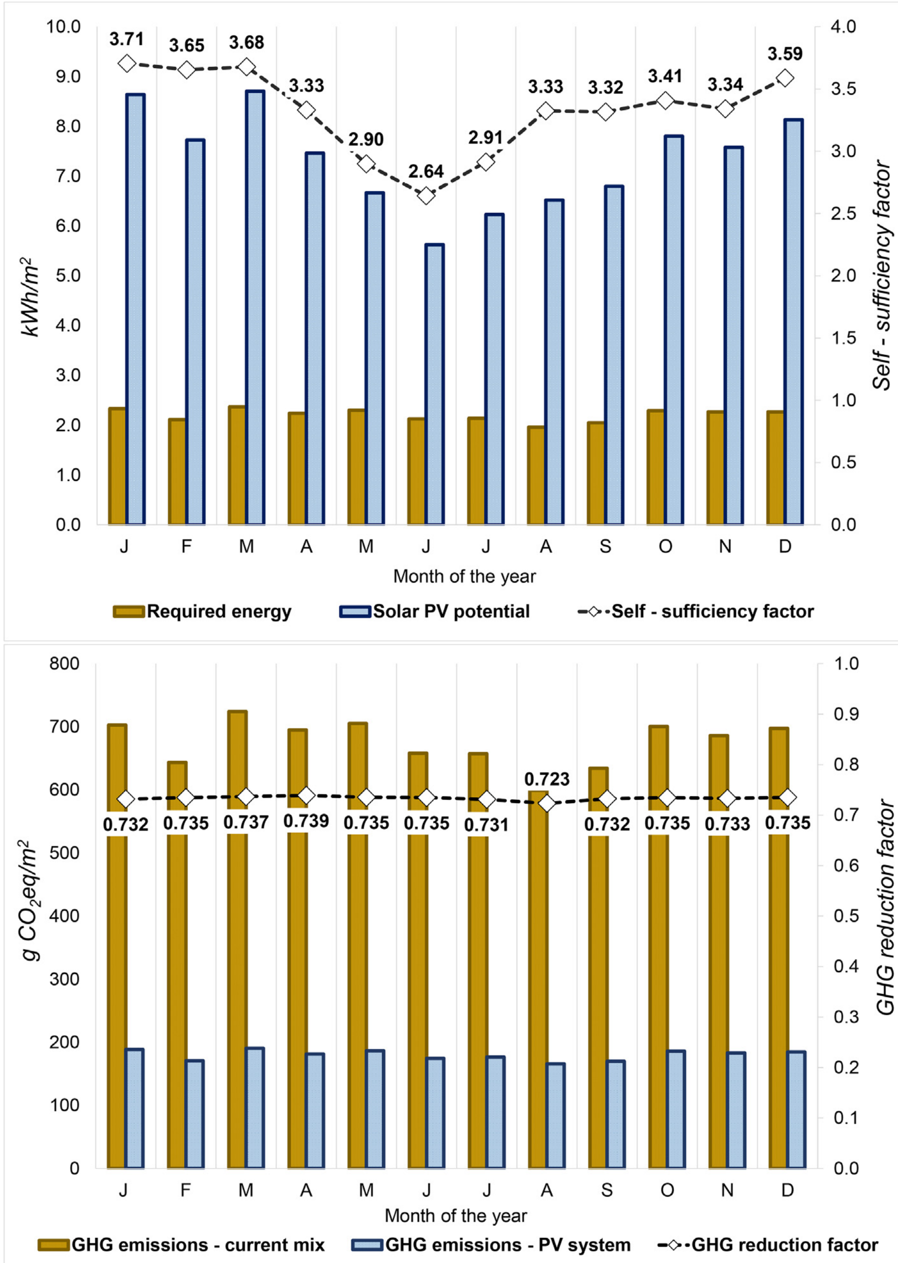

Fig. 8. Energy self-sufficiency potential through the use of underutilized rooftop area for photovoltaic energy production in the city of Ica (8a); and derived GHG emissions mitigation as compared to current electricity grid emissions (8b).

this reduction alone is higher than the reductions that the Peruvian government has compromised in its Nationally Determined Contributions (NDCs) in the frame of the Treaty of Paris regarding distribution of energy with photovoltaic panels by 2030 for the entire nation, 15 kton CO_2eq per year (MINAM, 2015). In fact, land use changes, energy and transport have been identified as the most intensive sectors in terms of GHG emissions in Peru (INEI, 2015). Therefore, it appears that the implementation of decentralized photovoltaic technology in Peruvian cities could imply an important reduction in emissions, especially in coastal and Amazon areas of the country.

Beyond the GHG emission reductions detected within the system boundary considered in the LCA, we consider that the environmental benefits of implementing decentralized photovoltaic will most likely affect other environmental aspects, including particulate matter and photochemical oxidant formation (Laurent et al., 2012), especially in the Amazon basin where current electricity is based on fossil fuels. Furthermore, land use is an important credit in the proposed system, since the valorization of underutilized rooftop space in these urban environments implies an inherent optimization of urban and resources. Interestingly, the balance of system to store energy at night did not create significant additional emissions. Nevertheless, it should be noted that different battery types show different GHG emission values, as described by McManus (2012). Regardless of GHG emissions, however, it should be noted that these batteries (e.g., lithium ion, lead-acid…) can cause important environmental burdens in terms of human toxicity, eco-toxicity or metal depletion (Kabakian et al., 2015). Moreover, beyond the system boundary, the development of photovoltaic infrastructure on these previously existing rooftops avoids the placement of additional energy infrastructure in areas with high potential carbon losses (Hernandez et al., 2014). In fact, this would be of particular importance

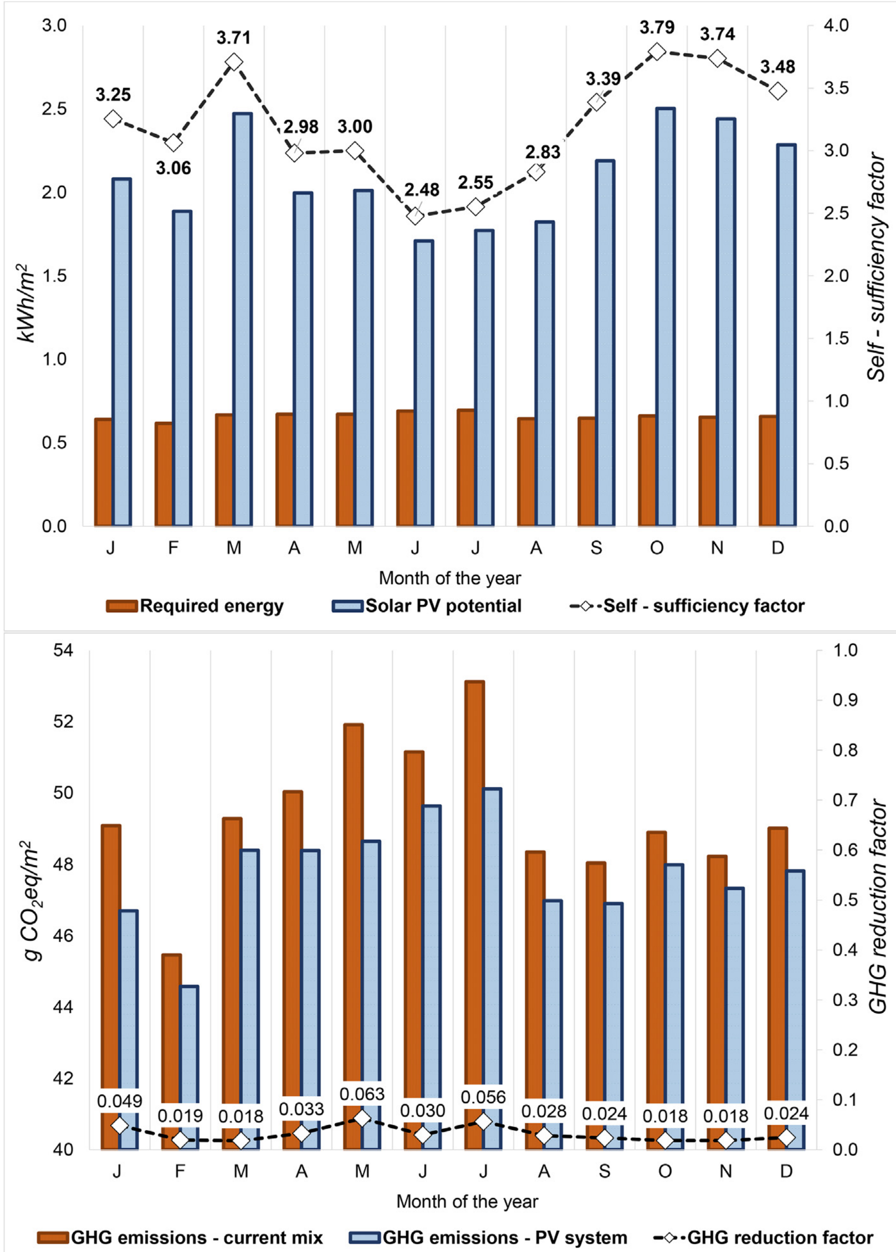

Fig. 9. Energy self-sufficiency potential through the use of underutilized rooftop area for photovoltaic energy production in the city of Ayacucho (9a); and derived GHG emissions mitigation as compared to current electricity grid emissions (9b).

in the Amazon basin, where peri-urban forested land can easily store up to 120 Mg of carbon per hectare (Asner et al., 2014). Therefore, new energy production and distribution infrastructure outside city limits can engender substantial GHG emissions due to land use change (Larrea-Gallegos et al., 2017).

Results suggest that photovoltaic solar energy obtained from underutilized rooftop areas would allow attaining full coverage of current electricity demand for residential, commercial and public lighting uses in all three cities. Nevertheless, it should be noted that medium-sized cities in developing and emerging nations have below average per capita consumption of electricity (IDB, 2011). In fact, electricity demand in the cities analyzed is not high, if data are compared to Lima. In the case of megacities like Lima, where demand for electricity is substantially higher, we hypothesize that the energy self-sufficiency factor would be significantly lower than that obtained in medium-sized cities. While medium-sized Peruvian cities are still absorbing urban growth through a steady sprawl, the city of Lima is experiencing two simultaneous phenomena: an increase in the vertical profile of the buildings, together with formal urban planning, along the modern Pacific façade thanks to the real estate boom, and a chaotic sprawl in other areas of the city with impoverished urban quality and deficient public services (García-Ayllón, 2016). In other words, larger cities will probably require more complex, multi-approach policy actions to achieve tangible climate change mitigation results.

Cities in Latin America do not tend to show high carbon emissions per capita for several reasons, including lower income per capita than in Europe or North America (Hardoy and Romero-Lankao, 2011; Ferroukhi et al., 2015). However, they do need to shift from carbon-locked policies in order to elude similar trends to those in industrialized countries (Cairns, 2014). Although several studies have discussed that global warming does not have a relevant space in the policy agenda in Latin America, it is fair to say that the current situation is changing due to the regional commitments related to the Treaty of Paris (Spikin and Hernández, 2016). More specifically, recent events in Peru, which

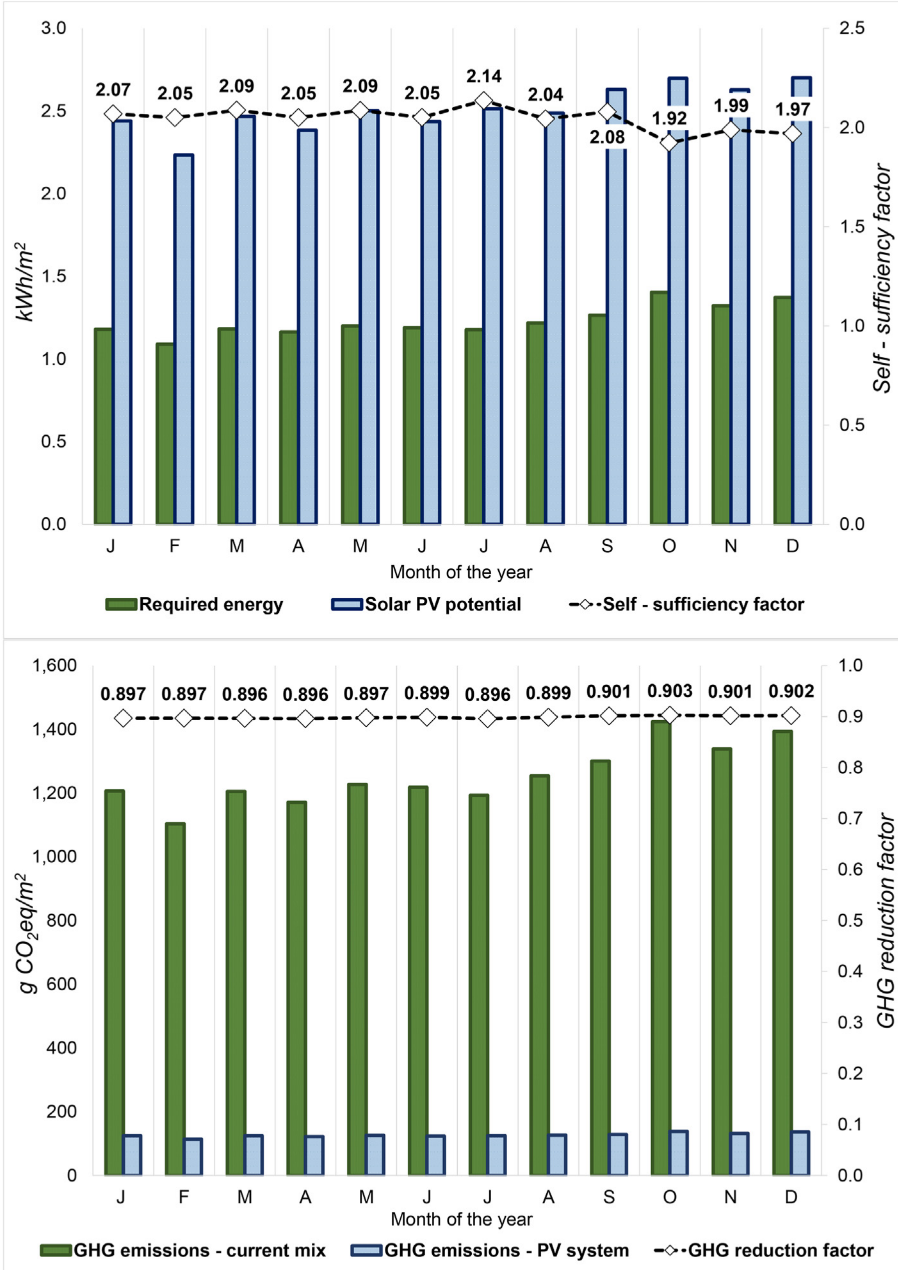

Fig. 10. Energy self-sufficiency potential through the use of underutilized rooftop area for photovoltaic energy production in the city of Pucallpa (10a); and derived GHG emissions mitigation as compared to current electricity grid emissions (10b).

left the city of Ica without water or electricity for days in March 2017, have visualized the vulnerability of the centralized water and energy systems to extreme weather conditions (El Comercio, 2017; Vázquez-Rowe et al., 2017). Hence, we venture that if decentralized urban renewable energy systems are brought into the market they could be seen as an attractive option to foster urban resilience and energy security.

At a technical level, there are important considerations to take into account for the implementation of solar modules. As indicated by Hernandez et al. (2014), it is convenient to analyze the environmental impact of these elements because they have the projection to be used in large numbers in the future. For instance, from an environmental perspective, effective albedo has been shown to be affected, with potential decreases in urban temperature of up to 0.2 °C (Taha, 2013). Other important issues in urban environments, such as dust generation and noise are also some of the issues being raised, although preliminary studies of these parameters in other cities show that their actual damage is negligible (Hernandez et al., 2014). Similarly, the feasibility of these modules would be highly dependent on adequate policy measures, including regional and urban governance and planning, which are discussed in Section 4.3.

4.2. Sensitivity analysis

The sensitivity analysis that was performed has the main objective of determining the robustness of the results computed in the study. In the first place, Scenario A1, as shown in Table 7, demonstrates that with the current urban morphology of these cities, residential population density would still have room for substantial increases in Ica (171%), Ayacucho (144%) and Pucallpa (100%), before the self-sufficiency factor reaches a

Table 7
Main results in each scenario of the sensitivity analysis.

	Unit	Ica	Ayacucho	Pucallpa
Current population density	pop./m^2	3.24E − 2	3.14E − 2	2.39E − 2
Scenario 01				
Maximum population density for a SSF of 1	pop./m^2	8.60E − 2	7.79E − 2	4.62E − 2
Percentage of variation of population density respect to current situation	%	171.40	143.66	100.45
Scenario 02				
Percentage of increase of SSF with an efficiency of 22% in solar modules	%	21.09	20.20	21.93
Scenario 03				
Maximum population density for a SSF of 1	pop./m^2	1.04E − 1	9.27E − 2	5.63E − 2
Percentage of variation of population density respect current situation	%	227.72	189.83	144.07
Scenario 04				
Annual percentage of increase in electric consumption per capita	%	0.712	1.46	0.3
Annual percentage of increase in residential population density	%	3.78	4.41	4.26
SSF factor in 2030[a]	–	1.42	1.07	0.88

SSF: self-sufficiency factor.
[a] The self-sufficiency factor is dimensionless.

value of 1. It is important to take into consideration that the height of buildings in these cities is relatively low, in a similar way to most cities in Peru (García-Ayllón, 2016). Furthermore, Peruvian cities tend to sprawl rather to become more compacted, which leads to the assumption that shifts in the vertical profile of these cities are not expected to suffer considerable shifts in the next few years.

Secondly, for Scenario A2, an increase from 18 to 22% in the efficiency of solar modules would also increase the electricity self-sufficiency factor by 20–21% with respect to the baseline scenario. While this result may be fairly evident, it demonstrates that under a ceteris paribus situation, the capability of these cities to obtain their electricity from solar modules would improve thanks to technological innovation.

When the previous scenarios are combined in Scenario A3, residential population density could be allowed to increase further as compared to Scenario A1. In other words, technological innovation in photovoltaic energy would progressively allow a shift to taller, more inhabited, buildings.

Finally, Scenario A4, which assumes a steady growth of per capita electricity demand and residential population density in the period 2015–2035, depicts a situation in which the cities of Ica (1.42) and Ayacucho (1.07) would still remain with sufficient self-generated electricity in solar modules to power urban activities, but for the case of Pucallpa the factor would be 0.88. This shows that the proposed installations are an interesting way to mitigate current GHG emissions, while improving energy security and resilience in these cities. However, long-term policies should aim at diversifying energy sources in these urban environments beyond the solar modules and the centralized grid system, to avoid falling in the trap on energy-reliance on one single source. Nevertheless, it is important to consider that urban planning is continuously subject to technological and social changes. Hence, although the scenarios modelled provide interesting projections for the future, the influence of novel technology and behavioral changes in society are not accounted for in the sensitivity analysis.

4.3. Future outlook

Considering that the self-sufficiency factor is above 1 throughout the entire year in the cities assessed, a substantial fraction of the electricity would be lost unless the surplus production is: i) sold to the electricity grid; ii) used for industrial activities within the city limits; or, iii) used to face expected increases in electricity demand in urban dwellings in the future. For these purposes, numerous countries have developed feed-in tariffs as regulatory instruments to promote renewable electricity, allowing a guaranteed sale to eligible producers, usually above the market price (Stokes, 2013). However, similarly to what occurs in most of South America, this widespread instrument in Europe or Asia is not implemented in Peru (IRENA, 2015). Nevertheless, Peru incorporates a series of feed-in tariff elements in its periodical renewable energy auction system (IRENA, 2015, 2014). Interestingly, regional governments in Peru are the reference authority in terms of land use planning, which includes the identification of adequate areas to implement renewable energy concessions with an installed capacity below 10 MW. With a correct coordination with local authorities, and improved conditions for small-scale producers, we argue that the existing policy framework could allow the regions to support the implementation of solar modules in urban rooftops.

Nevertheless, regardless of energy production in urban rooftops, it should be noted that underutilized rooftop areas could potentially host alternative or complementary infrastructure or technology to benefit from the endogenous resources available in the urban environment. For instance, rainwater-harvesting systems in rooftops would allow using this harvested rainwater for residential non-potable uses in those cities in which rainfall is substantial. Therefore, while the city of Pucallpa presents an average annual rainfall of over 1800 mm, allowing the consideration of such an infrastructure, in the city of Ica precipitation is close to zero, without sufficient precipitations to guarantee supply (SENAMHI, personal communication, May 2016).

5. Conclusions

Peruvian medium-sized cities have met a series of climatic and layout characteristics that would allow them to install photovoltaic panels in a range from 16 to 38% of the rooftop areas depending on the city selected. These values would allow these cities to be self-sufficient in electricity production for residential, commercial and public lighting purposes provided that these investments were to be performed in underutilized rooftops. For instance, the city of Pucallpa would be able to produce up to 5 MWh per capita under current demographic conditions.

Future plans regarding urban development in Peruvian, and by extension, other Latin American cities, must contemplate the implementation of solar photovoltaic energy in the rooftops of buildings. Beyond the benefits linked to attaining energy independence and security of this decentralized approach, our study demonstrates that substantial reductions in GHG emissions can be attained through this perspective as compared to the current situation. These reductions, however, would be highly dependent on the existing electricity grid mix in each region, demonstrating that decentralized urban photovoltaic systems would pose increased GHG emission mitigation in tropical Latin American urban environments in which hydropower is not the dominating electric source. Beyond the utility of this urban development scheme in cities of the Amazon basin, highly reliant on fossil fuels, or along the heavily-populated hyper-arid coast, were hydropower currently does not cover the full demand for electricity, we argue that this scheme

could be replicated in Caribbean islands, which also have an excessive dependence on fossil fuels. In parallel, decentralized photovoltaic systems may be an attractive and resilient option in the wake of natural disasters (i.e., earthquakes or mudslides), especially in the context of developing nations where the redundancy of centralized networks is limited.

The implementation of these photovoltaic systems in underutilized urban rooftops poses an attractive action in terms of climate change mitigation, dwarfing the iNDC actions stipulated by Peru in terms of solar energy in the electricity grid. Based on the results obtained, it appears plausible to establish investments to gradually reduce the dependence of medium-sized Peruvian cities from the national or regional electricity grid, increasing energy security, and reducing their carbon emissions. In addition, the installation of photovoltaic solar systems demonstrates to be a reasonable strategy to revitalize underutilized rooftop areas in urban environments. However, for this to be reality, substantial changes in renewable energy policy must occur in Peru, together with improved urban planning and development.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.003.

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